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Price: £1.00

RAILWAY DIVISION

THE ADVANCED PASSENGER TRAIN

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Research, design and development for the APT (Advanced Passenger Train) are discussed from concept, through experiments with APT-E (Experimental), to the design of the commercial electrically powered APT-P (Prototype).

This paper is intended to be presented at an Ordinary Meeting of the Railway Division in London on Monday 13th December 1976 at 17.30h. Communications are invited for publication in the Proceedings. Contributors should read the instructions overleaf.

PROCEEDINGS 1976
VOLUME 190 62/76

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Synopsis The history and development of British Railways' Advanced Passenger Train (APT) are discussed. The technical objectives are considered in the context of their value to commercial and operating performance. Among the technical aspects discussed are dynamics of guidance and suspension, aerodynamics, power and transmission, braking, and lightweight body structures. Highlights of the research and development programme are described, with reference to laboratory and track testing of the experimental train (APT-E) and associated experimental vehicles. The paper concludes with a description of the design of the prototype electric train (APT-P), of which three are currently being constructed for operation on the London/Glasgow route.

Introduction

The Advanced Passenger Train (APT) originated as a by-product of several years fundamental research into the dynamic behaviour of railway vehicles. This research was initiated within British Railways (BR) during the early 1960s at a time when average operating speeds were increasing with the growth of diesel and electric traction, and when there was a world-wide reawakening of interest in means of reducing rail journey times.

Increased speeds had led to a worsening of vehicle riding qualities, particularly of two-axle wagons. Vehicle 'hunting' oscillations had long been recognised as a major limitation to satisfactory high speed running. Priority was thus given to solving this problem. Theoretical studies resulted in the development of a mathematical model which explained the phenomenon of hunting in terms of self-excited vibrations due to dynamic instability (1). More significantly, the important vehicle suspension and track parameters were identified and methods of avoiding instability devised. These methods were proved by designing a high-speed freight vehicle (2). This vehicle ran successfully at 160 km/h on the track and at 225 km/h on rollers in the laboratory.

The removal - or at least lifting - of the hunting barrier created the opportunity for designing vehicles which could operate satisfactorily at speeds higher than 160 km/h.

Parallel work on other aspects of dynamics provided an insight into how vehicles behaved on curves (3) and how they responded to both random and discrete track irregularities (4). A sound framework for understanding the interaction between vehicle and track was thus established.

This new understanding enabled the technical potential of the railways to be re-appraised and the economic feasibility of passenger travel at higher speeds recognised. From this came the concept of the APT in 1967.

APT Concept

The major attraction to inter-city rail passengers is shorter journey time (5). This was evident from the public's response to the improved services on BR's West Coast main line following electrification from London to Manchester/Liverpool, and from experience abroad, particularly on the Japanese Tokaido line. Comfort, reliability, safety and, of course, price and frequency of service are also important.

Shorter journey times can only be achieved through investment in new trains, in new infrastructure, or in both. BR's extensive and generally under-utilised railway network is the legacy of massive Victorian investment. The construction of new tracks or major new alignments would require further large investment and would absorb capital which might otherwise be available for trains. From the national viewpoint, therefore, it is preferable to exploit the existing assets to their full potential and concentrate effort on designing high-performance trains for existing tracks (6).

The obvious way of reducing journey time is to install more power and operate at a higher maximum speed. However, roughly 50% of BR's major routes is made up of curves, and of these about 50% are relatively sharp at between 0.5 and 2 km radius. Thus, average speeds of conventional trains tend to be determined largely by speed restrictions due to curves, and only modest gains can be made for a speed capability above 160 km/h on all except the straightest routes.

The major objective of APT therefore is to significantly raise operating speeds round curves, so that a high maximum speed results also in a high average speed.

Speed restrictions on curves are currently applied not for reasons of safety, but to limit the discomfort of passengers when subjected to centrifugal forces. The permitted speed is governed by the track radius and cant angle in conjunction with a limiting value of 0.7 m/s^2 for the net lateral acceleration. This corresponds to a maximum deficiency of about 4° in the cant angle.

APT aims to increase cant deficiency to 9°, equivalent to a net lateral acceleration of 1.5 m/s^2. This raises the maximum speed through curves by typically 20 to 40%, the exact speed ratio being proportional to the square root of the cant deficiency plus track cant angle.

Operation at these higher speeds would be intolerable for passengers in a conventional train. However, by tilting the APT vehicle bodies inwards by up to 9°, comfort is not only restored, but enhanced by fully compensating for cant deficiency.

For greatest impact on journey time, both maximum speed and cant deficiency must be raised (Fig. 1). Accordingly, APT performance boundaries are specified by 250 km/h and 9° cant deficiency.

Originally the APT was conceived as simply a high-speed passenger train, but the concept was subsequently refined, so attracting the name 'Advanced'. The broad objectives (7), in relation to the performance of the then existing trains, were to have a maximum speed 50% higher, to negotiate curves at up to 40% faster, to run on existing track with existing signalling, to maintain the standards of passenger comfort at the higher speeds, to be efficient in energy consumption, to generate low community noise, to maintain the levels of track maintenance, and to achieve a similar cost per seat-kilometre. In general, the aim was for APT to be as technically adequate at 250 km/h as the existing trains were at 160 km/h.

APT Programme

Because of the considerable technical innovation required for APT, a programme of research and development was planned to develop the theoretical background, to gather data about the track, aerodynamic and acoustic inputs, and to design and test hardware so that concepts could be proved in engineering terms.

This programme was authorised in 1969 and led to the construction of the gas-turbine-powered experimental train APT-E (8) (Fig. 2). Extensive laboratory facilities at Derby and a test track at Old Dalby were constructed (Figs. 3, 4). Also, other vehicles, including the two skeletal cars of APT-POP (Fig. 5) and the APT Hastings Coach(Fig.6), were built for testing particular items of equipment such as bogies, brakes and tilt suspensions.

When APT was first proposed it offered the promise of attractive advantages for inter-city travel, but at considerable technical risks. Also, it was evident that it would be several years before those risks could be resolved and the jump in technology consolidated. Therefore, not to lose commercial impetus, BR developed its high-speed strategy on the basis of first exploiting the potential of faster conventional trains and then exploiting APT. Accordingly, the decision was taken in 1970 to build the High Speed Train (HST) to improve journey times on the straighter major routes (9). Whilst using mainly established technology, HST did rely on the latest advances in vehicle dynamics theory to achieve stability up to its design speed of 200 km/h.

By 1973 the research and development programme had to a large degree proved the novel aspects of APT, and the technical risks were by then considered sufficiently small for it to be firmly integrated into BR's commercial plans. These required the APT to operate initially on the electrified West Coast main line, this being a curvy route where high cant deficiency performance is particularly attractive.

The design of a 25 kV electric prototype train APT-P was thus initiated, and in 1974 the construction of three trains was authorised. The first prototype is scheduled to start trials in 1977, and an experimental commercial service with the three trains is due to commence between London and Glasgow in 1978. These trains are the forerunners of a fleet of production APTs planned to start operation in 1981-82.

Guidance and Stability

The design of the APT suspension started from the recognition that guidance can be achieved by using coned wheels in conjunction with the creep forces generated by fractional deviations from pure rolling in the wheel-to-rail contact zones.

The guidance properties are improved by increasing the cone angle or conicity of the wheel treads. However, the guidance mechanism necessarily involves feedback (with the gain proportional to conicity), so that there is the potential for instability, leading to hunting. This results in a basic conflict between guidance and stability.

Another aspect of this conflict is found in the behaviour on curved track. Creep forces tend to steer a wheelset into a radial position, avoiding contact between flanges and rails. Furthermore, centrifugal forces can also be reacted by creep forces. However, if it is necessary to generate larger creep forces than are available from the coefficient of friction at the wheel tread, slipping will occur and guidance must then be provided by the flanges. For good steering on curves, the yaw and lateral suspensions should be soft. But, for good stability, they should be fairly stiff.

The resolution of the conflict between guidance and stability has been a fundamental objective of APT suspension design. This has been essential in order to attain a satisfactory ride quality and avoid excessive loadings on the track at high speeds, particularly on curves at high cant deficiency. The suspensions have thus been designed to be as flexible as possible, whilst retaining an adequate stability margin at 250 km/h with fully-worn wheel profiles having up to 0.3 effective conicity.

The ability to operate with worn-wheel profiles, besides improving guidance on curves, prolongs the interval required between tread reprofiling and, because of the better conformity between wheel and rail profiles, gives lower contact stresses and reduced wear rates.

The articulated configuration of APT-E was initially chosen to provide the maximum degree of geometric steering for the bogies, so that the demand on the available creep forces was minimised. However, since it was necessary to permit large rotations of the bogie when negotiating reverse curves, a form of yaw 'relaxation' suspension was necessary. This device - a high-rate hydraulic damper and series spring - was ultimately developed with a time constant which gave the requisite soft suspension for steering and stiff suspension for stability. Its adoption as the secondary yaw suspension for APT (and subsequently for HST), made the geometric steering feature of APT-E articulation obsolete. An articulated configuration, however, has been continued with APT-P, but in a somewhat different form, for reasons described later.

The guidance-stability conflict within the bogie itself has yet to be fully resolved, and development work is continuing with the application of yaw relaxation to the primary suspension. Operation of APT-E with primary relaxation at 230 km/h and at 12° cant deficiency has demonstrated the benefits in terms of reduced lateral track forces.

Tilt Suspension

The tilting of vehicle bodies by up to 9° has been a major influence on APT design. Tilt produces severe spatial constraints, controls many suspension parameters, and generates some of the dominant structural loading cases. The requirements for tilt were therefore fully integrated into the train design from the outset.

Because of the restricted space envelope prescribed by the BR loading gauge, the axis about which each vehicle must tilt is governed largely by the requirements for acceptable body width and profile (Fig. 7).

The existing transition curves between straight and constant-radius track are relatively short for high-speed operation, resulting in a demand for high tilt response rates up to 5 °/s. Such rates cannot be reached by a passive pendular type of tilt suspension, especially as the tilt centre nearly coincides with the body mass centre. Consequently, each vehicle is tilted independently by an active electro-hydraulic servo-system which responds to sensors measuring the lateral accelerations experienced by the passengers.

The gain of the system is chosen to give adequate stability margins whilst retaining an acceptable lag in response. The lag is limited so that the passengers are not subjected to transient lateral accelerations of more than 1.0 $\mathrm{m/s^2}$ (Fig.8) when entering or leaving a transition curve at the design maximum rate of change of cant plus cant deficiency of 8.3 °/s. The above value of acceleration can only be assured by avoiding contact with the lateral suspension bump-stops. This is also necessary if high dynamic forces are not to be transmitted to the track.

It is essential that higher curving speeds do not cause excessive overturning moments. Accordingly, the maximum quasi-static transfer of load from inner to outer wheels at 9° cant deficiency has been specified as 33%, leaving an adequate safety margin for dynamics, side winds and so on. This value of load transfer compares with typically 20% for conventional vehicles at 4° cant deficiency. The overturning tendency for APT is minimised by having a low tilt centre and a low mass centre, which in normal operating conditions is maintained over the track centre-line by the tilt system.

The predicted overturning cant deficiency for APT is about 25°. To check this experimentally, a scrap coach, modified to simulate the mass and suspension properties of APT, was run at successively higher speeds round a 180 m radius curve near Dover until it overturned - at a cant deficiency of 24.3°. There was no evidence of any tendency to derail by flange-climbing, which supported the assessment that this mode of derailment was unlikely to be a problem at high cant deficiencies.

The objectives of the tilt development programme have been to optimise the conflicts between system response rates, stability, random ride quality and power consumption; to develop a system which retains safe and acceptable characteristics under failure conditions; and to attain a high reliability.

Development has resulted in some changes from the original tilt suspension configuration. The system embodied in APT-E exhibited static instability under 'soft' hydraulic failure conditions, so that devices were necessary to restrain vehicle bodies from flopping over onto the lateral suspension bump-stops. This problem has been overcome for APT-P by adopting a tilting bolster arrangement with inherent righting properties, so that a soft failure causes the body to adopt an upright position. This arrangement has been proven on the APT Hastings Coach.

Experience with APT-E has confirmed that failure of a vehicle tilt system need not affect train reliability in terms of completing a journey on time. Numerous tests have been carried out at 9° cant deficiency with a vehicle purposely tilted by 9° in the 'wrong' direction. These have shown that even a 'hard' failure of the tilt system, whilst discomforting to passengers, is not unsafe. Very infrequent operation in a tilt-failure mode is thus tolerable, and discomfort can be mitigated by evacuating passengers to other vehicles.

Interaction with Track

In designing a high-speed train for operation on the existing track, it was obviously important to define that track in quantitative terms appropriate for rational vehicle design. Specialised data was therefore acquired by conducting a track survey at 25 sites, each 3.2 km long, chosen at random from 4 500 km of BR main-line track.

Measurements were taken of track and rail geometries and, using a specially-developed track-measuring machine, vertical, lateral and cross-level track roughnesses were measured and defined in statistical terms. In addition, surveys were carried out to define the frequency, shape and severity of the discrete irregularities associated with rail joints and crossings.

The resulting information enabled the design inputs to APT suspensions to be specified and enabled fatigue and proof loading cases for structural components to be formulated.

To attain a high standard of comfort in response to random track roughness, APT has been designed with very soft suspensions having vertical and lateral natural frequencies of 0.7 to 0.8 Hz. The measured body accelerations, at speeds up to the maximum of 244 km/h reached by APT-E, have been consistent with the target values, for average good-quality main-line track, of 0.3 $\mathrm{m/s^2}$ r.m.s. vertical and 0.2 $\mathrm{m/s^2}$ r.m.s. lateral, when weighted in accordance with the ISO constant comfort curves.

Unless counteractive steps are taken, the track becomes more highly loaded at high speeds, resulting in more track damage and maintenance. The first contribution to vertical loading is the static axle-load, which for APT is specified as 170 kN maximum. However, at high speeds, dynamic loadings can become large compared with the static load, especially at rail joints and crossings. The impacts have two components (10) : the P1 force due to a high frequency (500 to 2 000 Hz) bounce on the Hertzian contact stiffness between wheel and rail, and the P2 force due to a lower frequency (20 to 100 Hz) bounce of the wheelset on the track foundation stiffness. The P2 force is the dominant cause of damage and leads to progressive deformation of the track.

To limit impact forces to an acceptable level, unsprung mass must be reduced roughly in proportion to speed-squared. The criterion for acceptability on BR is the Class 55 Deltic locomotive at 160 km/h with an unsprung mass of 3.3 Mg. The acceptable unsprung mass for the APT at 250 km/h is 1.5 Mg. (This compares with 2.2 Mg for the HST at 200 km/h).

Early in the development programme APT-POP was fitted with resilient wheels to reduce the P2 forces. These wheels were found to be unsuccessful at high speed, however, because they were torsionally soft and thereby gave rise to dynamic instability. As the target unsprung mass can in fact be met without resilient wheels, it is not intended to fit them to APT-P, unless it is ultimately shown that P1 forces prescribe an operating limit. These forces could then only be satisfactorily controlled by fitting a torsionally stiff resilient wheel with a very low tread mass.

Following an impact at say a rail joint, there is a rebound period when the wheels tend to leave the rails, causing at least a momentary loss of adhesion. This problem increases rapidly with speed and has needed careful bogie suspension design to ensure that the energy of the impact is dissipated quickly enough to avoid lift off.

Operation of APT at higher speeds on curves causes higher centrifugal forces. Whilst these can be compensated for the passengers - by tilting the vehicle bodies - they are experienced in full by the track. Consequently, APT's higher quasi-static forces are for the track the most significant departure from conventional experience. An extensive experimental programme has therefore been undertaken to investigate this fundamental aspect of the interaction between APT and the track.

The track is held in position mainly by friction between sleeper and ballast. However, tests have shown that instead of there being simply a threshold force at which gross permanent deformation is initiated, all lateral rolling loads cause some hysteresis, resulting in some sideways creep of the track. The creepage rate increases with load and diminishes as the track is consolidated with traffic after tamping. Acceptable performance tends to be determined by maintenance rather than safety criteria.

To gain some insight into long-term effects, APT-E (Fig.9) has undertaken long series of repeated runs round a 1.15 km radius curve on the test track at speeds up to 195 km/h, corresponding to 12 ° cant deficiency. Tests were carried out with the track repeatedly tamped and in various degrees of consolidation. Measurements were taken of track displacements, bogie lateral forces (H-forces), and track lateral forces (Y-forces), using both load-measuring wheels and load-measuring track base-plates. Force measurements have also been taken during numerous runs by APT-E on the Midland main line between London and Leicester at speeds up to 200 km/h and at cant deficiencies up to 10.5 °. These tests have established confidence in the ultimate acceptability of APT fleet operation at 9 ° cant deficiency.

In designing APT for high curving speeds, the aim has been to achieve low unsprung and bogie masses in comparison with the supported body mass. This ensures that the steady sideways forces plus the dynamic forces resulting from track imperfections are minimised relative to the axle-load, which is the major track stabilising force.

This design approach, and the limitation on unsprung mass, has had considerable influence on the choice of APT configuration and disposition of equipment, particularly braking and transmission equipment. A basically articulated train formation has been adopted, with adjacent coach bodies sharing bogies, so giving a high ratio (between 3:1 and 4:1) of axle-load to half-bogie weight. The choice of an articulated configuration harmonises with other objectives for APT, including good stable riding qualities, reduced train mass, low energy consumption, low wheel-rail noise generation, and reduced bogie costs.

Train Performance

At high speeds the major source of train resistance is aerodynamic drag, which increases as speed-squared. Consequently, the energy and power used in traction tend to rise rapidly as operating speeds are increased.

Although train weight has only a small effect on energy consumption at constant speed on level track, its effects are important when climbing hills and during accelerating and braking. Train weight influences particularly the number of powered axles, and hence the amount of power equipment, required for operation at acceptable adhesion levels.

For economic performance, therefore, APT has adopted a streamlined low-drag profile and lightweight construction. Since the effect of acceleration rate on inter-city journey times is of secondary importance, only sufficient power is installed to give a train balancing speed on level track about 5% above the maximum operating speed.

The low aerodynamic drag of APT results from its nose and tail shape, its reduced cross-section including lower roof height, and its general surface smoothness. Drag measurements with APT-E have confirmed that at 160 km/h APT consumes only two-thirds the energy of a present-day train (Fig. 10). Put another way, APT uses the same energy at 200 km/h as existing trains do at 160 km/h.

Improved aerodynamic performance also attenuates the pressure pulses caused when entering and leaving tunnels, and when passing other trains and track-side structures. Similarly, slipstream wind effects are attenuated, so reducing track-side gusts. The effects of higher speeds are therefore at least partially compensated. Measurements with APT-E have shown that, compared with present-day trains, equivalent pressure pulses are generated in tunnels at 17% higher speed, and equivalent track-side gusts are produced at 40% higher speed.

Speeds through some tunnels are restricted, to avoid transient pressure changes of greater than the discomfort threshold of 3 kN/m^2 in 3 seconds. Passengers in APT-P will experience still lower pressure pulses than passengers in existing trains, because vehicles will be sealed before entering tunnels.

The objective of low train mass has been achieved by constructing trailer car bodyshells in aluminium alloy, by fitting lightweight equipment, and by adopting an articulated train configuration, thereby eliminating roughly half the number of bogies. The total weight saving per passenger seat compared with a conventional train is about one-third. Further significant reductions in weight would not be practicable because of the increased risk of overturning in extreme wind conditions.

It is noteworthy that the drag and weight reductions produced by articulation alone can reduce energy consumption by some 15% and reduce journey times by about 3%.

A further advantage of articulation is that it cuts the total noise generated between wheels and rails - which is the major source of noise at high speed - by about half. Because of this, and because of improved suspension design, the track-side noise level experienced by the public will be 5 dBA less at 160 km/h compared with present trains. The noise level will be no worse with APT at 250 km/h than present trains at 160 km/h.

Improved energy performance stems also from APT's capability for higher curving speeds. The energy consumption when operating with cant deficiencies up to 9° differs little from when operating with up to 4°. This is because the train has to slow down less often for speed restrictions, and so wastes less energy in braking and re-accelerating. By achieving much shorter journey times, however, the energy is used more effectively.

Although APT-E has run at a maximum speed of 244 km/h on the relatively straight London to Bristol route, its major performance demonstration has been on the restrictively curvy London to Leicester route which benefits considerably from APT's high curving speeds (Fig.11). Operating at a maximum speed of 200 km/h, except for a short stretch at 215 km/h, it has completed the 159 km journey in 58.5 minutes, that is, at an average speed of 163 km/h. This is equivalent to a service timing of 1 h 02 min, which compares with the best present-day timing of 1 h 24 min.

Power and Transmission

Automotive gas turbines were adopted as the power units for APT-E. In 1968 British Leyland, in common with many of its international competitors, was actively developing a gas turbine with regenerative heat exchangers for possible application in the 1980s. The decision to evaluate the Leyland experimental engine in APT-E was based on an assessment of the potential benefit to the railways if successful development eventually led to mass production and hence to low-cost power units.

Gas turbines have the advantages of compactness and lightness. Thus, compared with diesel traction, and in common with electric traction, gas turbine traction potentially enables twice as much power to be accommodated within the space and weight constraints of a given vehicle.

The world oil crisis of 1974 was largely responsible for Leyland's suspending its turbine development programme, for, even with successful heat-exchanger development, the fuel consumption of the gas turbine would be marginally higher than that of a comparable diesel engine. Nevertheless, APT-E successfully completed its programme using five turbines per power car, some of which ultimately delivered over 260 kW. The troublesome heat-exchangers were eventually removed once it was clear that they would not materially contribute to the APT experimental programme.

The decision to use 25 kV 50 Hz electric traction for APT-P followed from decisions on business strategy and was not in any way dictated by power-plant problems. This strategy required the first application of APT to be on the West Coast main line, which is electrified. An APT for non-electrified routes is now likely to be diesel-powered, since the successful production of a suitable regenerative gas turbine cannot yet be foreseen.

The power transmission system for APT-E employed conventional axle-hung d.c. electric traction motors. This arrangement was adopted as a short-term expediency because of timescale difficulties. It was fully recognised, however, that its excessive and unrepresentative unsprung mass was unacceptable beyond the experimental stage. A completely different transmission arrangement has, therefore, been developed for APT-P (Fig. 12).

The additions to unsprung mass and bogie mass are minimised by using flexible axle-drive quills and by mounting the separately-excited traction motors in the power car body. Power is controlled by thyristor convertors and is transmitted independently to each driven axle via a body-mounted gearbox, cardan shaft, and lightweight final-drive reduction gearbox. The final-drive gearbox is fully suspended on the bogie frame.

An advanced design of pantograph, with three-stage suspension, is being developed for APT-P. This is mounted on an anti-tilt mechanism which maintains the pantograph head over the track centre-line. Although the pantograph is restrained to the bogie in roll, it is otherwise fully suspended with the vehicle body.

Braking

The braking system for APT is designed to stop the train from 250 km/h within the existing signalling distances for 160 km/h trains, including a 12.5% margin.

Hydrokinetic brakes were chosen (11) to meet the arduous braking duty because they were capable of dealing with the very high levels of energy dissipation (35 MJ per trailer axle) and power dissipation (1.5 MW peak per trailer axle), whilst complying with the limitations on unsprung mass and bogie mass. The combination of high energy, high power, and low unsprung mass makes conventional friction brakes unattractive.

The hydrokinetic brake (Fig.13) develops a torque, when filled with fluid, in the same way as the familiar engine dynamometer. The brake is mounted inside a hollow axle on all except driven axles, and the energy of braking is converted into heat as angular momentum is successively generated and destroyed within the fluid. The torque produced is proportional to the pressure rise through the brake; regulation of this pressure thus provides a simple means of controlling torque. The fluid (water-glycol) is pumped by the brake itself to a body-mounted reservoir, and the heat is subsequently dissipated in fan-cooled radiators. The continuous power rating for the brake on APT-P is 6 W/kg of train mass.

Because the hydrokinetic brake loses its effectiveness at low speeds, an auxiliary light-duty hydraulic friction brake acting on the wheel treads is also provided. This brake is automatically blended in at speeds below 80 km/h.

Although rheostatic brakes have been used on APT-E powered axles, each powered axle on APT-P is hydrokinetically braked, the brake being fitted to the body-mounted gearbox in the mechanical drive to the axle (Fig. 12).

The hydrokinetic brake has been exhaustively tested on a brake dynamometer in the laboratory. The tests have shown the brake to have a highly-repeatable flat braking characteristic and an inherent freedom from wear. APT-E has consistently demonstrated the effectiveness and smoothness of the brake from speeds above 200 km/h at up to its design average deceleration rate of 1.4 m/s^2. Also, nearly 300 000 km of endurance running has been completed by a hydrokinetic brake fitted to a conventional vehicle operating in a regular main-line service.

Although APT is capable of average deceleration rates of 1.4 m/s^2, the maximum rate which is operationally acceptable at present is, as for HST, 0.9 m/s^2 - because of potential adhesion limitations. This restricts APT to 200 km/h on many sections of track. Ultimately, the restriction may be relaxed if, as is expected, APT improves the usage of available adhesion. Improvements should derive from the uniform characteristics of hydrokinetic brakes, the use of adaptive wheel-slide control, and improved vertical and lateral vehicle dynamics.

Vehicle Structures

Lightweight vehicles are required not only for low total train mass but also for acceptable axle loads, especially on articulated axles. To meet the mass targets, APT trailer car bodyshells are constructed in aluminium alloy, giving a 40% weight saving over a conventional steel coach. Lightweight steel construction has been adopted for power car bodyshells.

The vehicle structures are designed to meet the UIC loading specification for main-line coaches, including the 2 MN proof buffing load. They are also designed to be stiff enough to avoid strong vibration coupling between body and bogie frequencies. The dominant design criterion tends to be stiffness rather than strength, as high flexural natural frequencies are essential for good ride quality at high speed. APT body structures are therefore designed for fundamental lateral and vertical bending frequencies of about 15 Hz when fully equipped.

The trailer cars of APT-E were designed as efficient semi-monocoque structures incorporating deep structurally-effective underbellies. When constructed, they confirmed that the strength, stiffness, and mass targets could be achieved. The structural principles were proved to be sound, but the method of construction, using aircraft practices and close-pitch riveting, was not economic for quantity production. Thus, a method of construction was sought which offset the high material costs of aluminium by reduced labour costs. The target was to produce an aluminium shell for the same cost as a conventional shell.

The form of construction adopted for APT-P is based on extensive use of wide commercial-grade aluminium extrusions running the full length of the vehicle and making up the outer profile (12). These are seam-welded together automatically. The completed bodyshell has a mass of 4.8 Mg. As part of the development programme, a pre-prototype shell was built to prove the production methods. Structural and resonance tests confirmed that the design strength and stiffness requirements were met (Fig.14).

The power cars of APT-E were designed as simple steel space-frame structures with non-load-bearing skins so that modifications could be accommodated easily during the experimental programme. Indeed, at one stage the power cars were lengthened to improve dynamic stability.

The APT-P power car is a steel semi-monocoque structure with deep side skirts. High stiffness is attained with an efficient distribution of mass, resulting in a bodyshell mass of only 12 Mg.

A feature of the articulation arrangements for APT-E was the use of a spherical pivot between adjacent vehicle bodies. This led to the fundamental bending frequencies being severely depressed, with subsequent penalties on structural vibration levels. On APT-P this problem has been avoided by adopting a form of articulation which allows relative movements between vehicle ends. This improvement, along with those stemming from the secondary yaw and tilt suspension developments, has led to a simpler and lighter articulated bogie design (Fig. 15).

Passenger access on APT-E was via doors in a separate 'joint module' between vehicles which was integrated into the articulation mechanism. With the change in articulation arrangement, passenger doors on APT-P have been incorporated into the main vehicle structure. By having only two wide doors per vehicle, located in diagonally opposite corners, it has been possible within a total vehicle length of 21 m to accommodate 72 second-class or 47 first-class seats at standard pitch.

Internal fittings such as seats, luggage racks and trim panels are modular and easily replaceable. Similarly, air conditioning, tilt control and brake control units are installed in the vehicle underbelly as pre-commissioned, readily-removable packs.

Substantial weight savings have been achieved by developing a chemical toilet, lightweight seats (12 kg/second-class seat), and a low-energy air conditioning system. This system uses a low fresh air charge and a high (80%) re-circulatory flow, de-odorised by carbon filters. The small intake and exhaust areas are sealed on entry to tunnels to protect passengers from transient pressures.

The passenger noise environment inside APT is required to be not more than 68 dBA and 76 dBB. These values have been adequately demonstrated in a trailer car section of APT-E. Acoustic studies and measurements have assisted in an efficient disposition of sound insulation material in APT-P. This has included an optimisation of the trade-off between reduced structure weight and increased sound-proofing weight.

25 kV Electric Prototype APT

The 25 kV electric APT comprises two rakes of articulated trailer cars between which are positioned one or two power cars. Each trailer rake consists of a number of two-axle intermediate cars and two three-axle end cars. Each power car has four axles, each with a continuous tractive power rating of 750 kW. Power cars and trailer rakes are easily uncoupled from each other in order to satisfy operating and maintenance requirements.

The train can be formed into three alternative versions (Fig. 16) (Tables 1 and 2). The choice of version, and of number, type and disposition of trailer cars, depends on the commercial and operating requirements for a particular service. The 200 km/h (1+11) low-powered version, with 11 trailer cars, represents the longest train that can be hauled by a single power car up the 1.5% gradients on the West Coast main line. The 250 km/h (2+12) high-powered version, with 14 vehicles total, is the longest train which can be accommodated within existing platform lengths. The 250 km/h (2+14) 'stretched' version is the longest formation envisaged. Its application would require some investment to lengthen platforms. However, it has the advantages of high capacity and high-speed capability at a similar cost per seat-kilometre to the (1+11) version.

The (2+12) version has been adopted for the prototype train APT-P so that the full design performance can be proven. By re-marshalling vehicles, the other versions can also be tested. When APT-P enters experimental commercial service, the maximum speed will be limited to 200 km/h, giving a possible journey time of 3 h 57 min from London to Glasgow with one intermediate stop. This compares with the best present-day timing of 5 h 00 min. It is probable that fleet service will be initiated with the (1+11) version at 200 km/h, retaining the option for two-power-car versions and higher speeds when commercially and operationally justified.

The train configuration, with power cars positioned in the middle, has been adopted for a number of reasons. Firstly, experiments have shown that the collection of current with more than one pantograph is likely to be unsatisfactory at 200 km/h with existing overhead equipments, particularly sagged-simple equipment. There are, therefore, advantages in locating two power cars adjacent to each other, with current being collected by a single pantograph and transmitted locally between power cars by a 25 kV link. Secondly, excessive train buckling forces would be generated under propelling conditions if two power cars were to be positioned at one end of the train. Thirdly, by avoiding the need to fit a cab and heavy buffing and drawgear to the power car, it has proved feasible to install, within the severe vehicle mass limit of 69 Mg, sufficient thyristor-controlled traction and auxiliary power equipment to give a total power output of 4 MW. Consequently, the (1+11) version is able to achieve 200 km/h with only its one power car. Fourthly, for operational flexibility, it is advantageous to have two relatively short equal-length rakes of articulated trailers rather than one long rake. The use of a central power car permits this with the minimum addition to train mass and with the minimum number of vehicle types.

Communication between the two trailer rakes is normally available to staff only, via a corridor through the power car. Passengers will be permitted access only in emergencies and when escorted by a member of staff. To minimise this disadvantage, each rake of trailer cars is self-contained, incorporating both first-class and second-class accommodation and catering facilities. First-class accommodation is always towards the middle of the train and second-class towards the ends, the division being marked by the intermediate catering car. The catering unit provides full meals for first-class passengers in their seats and a buffet service for all passengers.

Auxiliary power generation equipment for the train is carried at the two ends of each trailer rake, thereby improving overall weight distribution. A 400 kW motor-alternator set is mounted in each trailer car next to the power car. This vehicle also accommodates a parcels van and guard's compartment. A 200 kW diesel-alternator set is mounted in each driving trailer car, behind the cab. This set provides power during emergencies and when the train is towed on non-electrified lines during planned diversions. To facilitate towing, the cab, which is similar to HST's in internal layout, carries a frangible nose section which can be hinged upwards to reveal conventional buffers and drawgear.

So that higher curving speeds can be safely exploited, a display in the cab advises the driver of the permitted maximum speed for APT at any instant. The system is based on transponders (passive micro-electronic receiver and transmitter devices) which are mounted on the track at intervals. These transmit coded speed limit information to the train as it passes over them. A driver can thus drive APT using the speed limit display in conjunction with his standard route knowledge only. Advance warnings of permanent speed restrictions are given to indicate when braking should be initiated. Whenever the display is blanked out, the driver must obey standard speed limits. These apply, for instance, at the approaches to terminal stations.

Speed Potential for APT

The APT has been designed for a maximum speed of 250 km/h; with relatively minor modifications it could run at 300 km/h. The maximum worth-while speed, however, is determined not simply by technical capability but by commercial and social factors. Higher speeds are worth while until revenue rises more slowly than costs, or until the economic, social and environmental advantages to the nation grow more slowly than the disadvantages.

APT's ability to curve at 9 ° cant deficiency enables average speeds on existing BR tracks to be raised by typically 20 to 25%, further increases again being inhibited by speed restrictions due to curves. Most journey time benefits are, therefore, gained with maximum speeds of 200 to 250 km/h for APT compared with 160 to 200 km/h for conventional trains.

On three primary routes (Table 3) (Fig.1), the rates of journey time reduction for APT become progressively lower as 250 km/h is approached, and the energy consumptions become progressively higher. Thus, based solely on considerations of time saving and energy consumption, the maximum worth-while speeds on primary routes tend to limit at around 225 km/h, the straighter routes benefitting to the highest speeds. To obtain further reductions in journey time, improvements to track alignments and increases in track cant angles tend to be more rewarding than increases in maximum speed alone. However, such improvements could consequentially raise the maximum worth-while speed to 250 km/h.

It follows that speeds above 250 km/h should only be considered in the context of important new routes with very large radius curves. With the cancellation of the Maplin Airport and Channel Tunnel projects, no application for a very high speed APT is foreseen.

On secondary routes, APT's capability for higher average speeds can be fully exploited at a maximum speed of 200 km/h or less, depending on the curviness of the route.

The type of traction has a considerable influence on the maximum speed that is worth while on a particular route. Financial benefits are enjoyed to a higher speed on electrified lines because of the better output power-to-weight rating of an electric power car compared with a diesel - roughly 40 W/kg compared with 20 W/kg. Therefore, whereas speeds approaching 250 km/h are likely to be commercially worth while for an electric APT, the maximum worth-while speed for a diesel APT is likely to be about 200 km/h.

Independent of the type of traction, APT is able to exploit the potential of existing tracks and also maximise the benefits available by improvements to the infrastructure. The fundamental feature of APT - its ability to negotiate curves faster - goes some way towards the ideal of a constant speed railway, subject to only a single speed limit. This results in the most economical use of energy in the attainment of shortest journey times.

Acknowledgements

The authors are grateful to Mr.G.S.W.Calder, Chief Mechanical and Electrical Engineer, British Railways Board, and to Dr.K.H. Spring, Head of Research, for permission to publish this paper. The views expressed are those of the authors and not necessarily those of the British Railways Board.

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This paper is intended to be presented at an Ordinary Meeting of the Railway Division in London on 13th December 1976. The MS was received on 21st June 1976 and was accepted for publication on 30th June 1976. 12

Train Formation	Tractive Power MW	Mass		Length m	Balance Speed km/h	No. of Seats		
		tare Mg	laden Mg			1st class	2nd class	total
(1 + 11)	3·0	370	417	253	215	144	376	520
(2 + 12)	6·0	463	515	294	270	144	448	592
(2 + 14)	6·0	509	572	336	255	144	592	736

Table 1: **25 kV electric APT : train parameters**

Vehicle Type	Vehicle Description	Mass		Length m	Class	No. of Seats
		tare Mg	laden Mg			
SD3	driving trailer car	34·6	38·7	21·5	2nd	52
S2	intermediate trailer car	23·0	28·6	21·0	2nd	72
SC2	catering trailer car	26·4	28·6	21·0	2nd	28
F2	intermediate trailer car	23·8	27·5	21·0	1st	47
FV3	van trailer car	31·2	36·2	21·1	1st	25
EP4	power car	–	69·3	20·4	–	–

Table 2: **25 kV electric APT : vehicle parameters**

APT Formation	Line Speed Limit	London – Glasgow 1 stop (Preston)		London – Edinburgh 1 stop (Newcastle)		London – Bristol 1 stop (Bath)	
		Time	Energy	Time	Energy	Time	Energy
	km/h	h min	MW h	h min	MW h	h min	MW h
(1 + 11)	160	4 38	7·2	4 24	7·0	1 25	2·1
	200	4 05	9·7	3 48	9·2	1 13	2·8
	225	4 03	9·9	3 45	9·5	1 12	2·9
(2 + 12)	160	4 35	8·8	4 22	8·4	1 24	2·6
	200	3 57	12·4	3 46	12·0	1 11	3·5
	225	3 49	14·4	3 34	14·0	1 07	4·0
	250	3 46	15·7	3 28	15·5	1 04	4·4
Best 1976 / 77 time - table	160	5 00	9·7	5 33	–	1 47	–
	200	–	–	–	–	1 32	–

Table 3: **Performance of 25kV electric APT on three primary routes: effect of maximum permitted speed on journey time and on energy consumption. (Energy includes that usefully consumed in traction, auxiliaries and vehicle tilting.)**

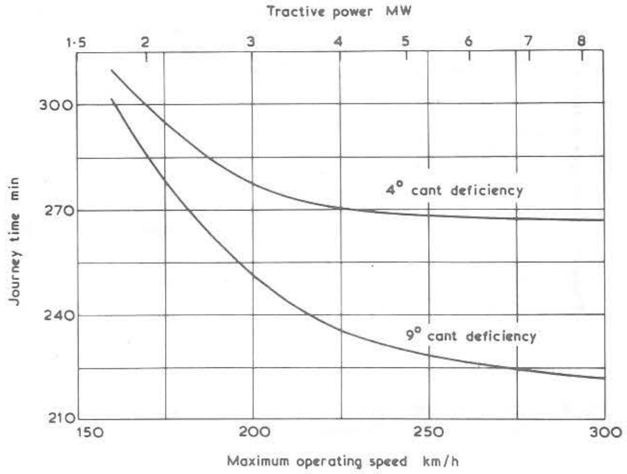

Fig. 1: Effect of maximum speed and cant deficiency on journey time from London to Glasgow for 14-vehicle APT of mass 474 Mg. (Note: power is adjusted to give balancing speed 5 per cent higher than maximum operating speed; journey includes two intermediate stops.)

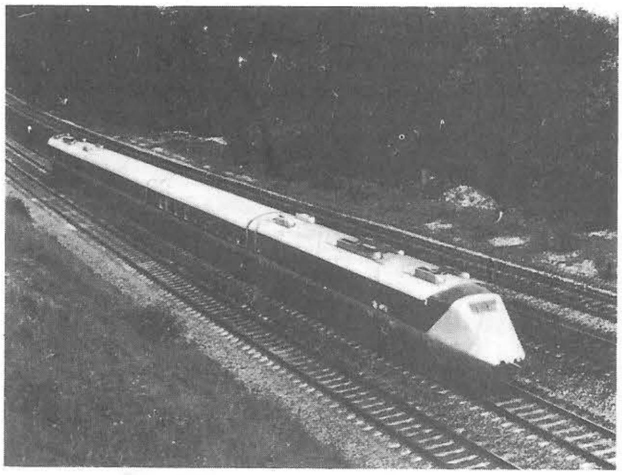

Fig. 2: The articulated experimental train APT-E comprises two power cars, each powered by five automotive gas turbines, and two trailer cars. One car is fitted with instrumentation, including on-line computing facilities, for performance monitoring; and one is fitted out for subjective ride assessment and acoustic studies

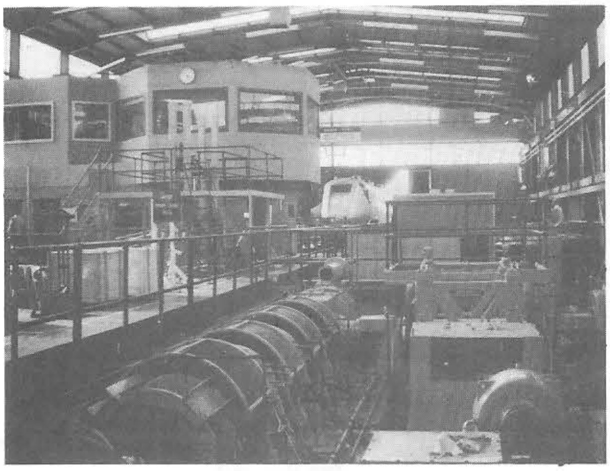

Fig. 3: The laboratory built for APT development at Derby houses experimental rigs, including extensive hydraulic test equipment, a brake dynamometer (foreground), a mechanical transmission dynamometer and a six-axle roller rig. The control tower (left) houses controls and instrumentation, including a mini-computer, for conducting major experiments

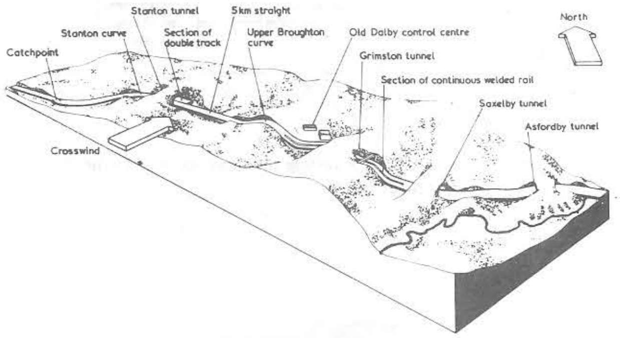

Fig. 4: The 20 km length of single-line test track follows the alignment of the closed Nottingham to Melton Mowbray line. Much of the track is of continuously welded rails on concrete sleepers. However, sufficient stretches of the original jointed rails on wooden sleepers remain, notably the 5 km straight and Stanton curve, to provide 'worst-case' conditions. The double track in Stanton tunnel allows an instrumented aerodynamics coach to stand in the tunnel whilst APT passes. (Fig. 9 shows APT-E on the Upper Broughton curve.)

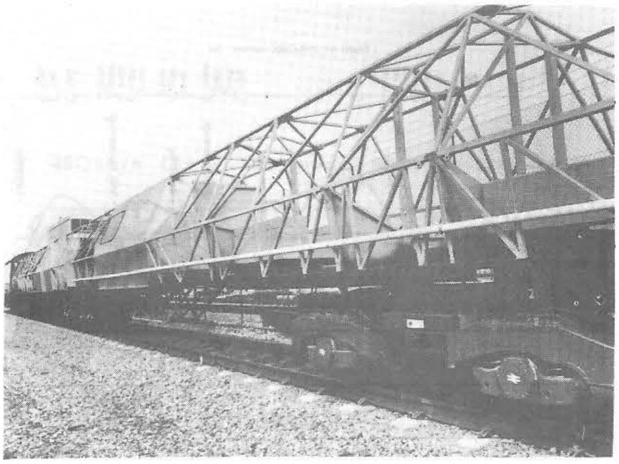

Fig. 5: The two APT-POP articulated vehicles embody simple space-frame structures for testing bogies and suspensions at speeds up to 200 km/h

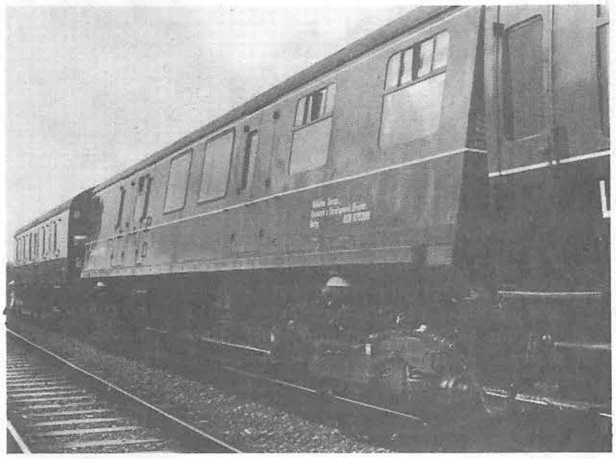

Fig. 6: The APT Hastings Coach (the body originated from the London to Hastings line) is mounted on pre-prototype end trailer bogies. Its narrow body width enables tilt suspension tests to be carried out on the main line with up to 6° tilt angle

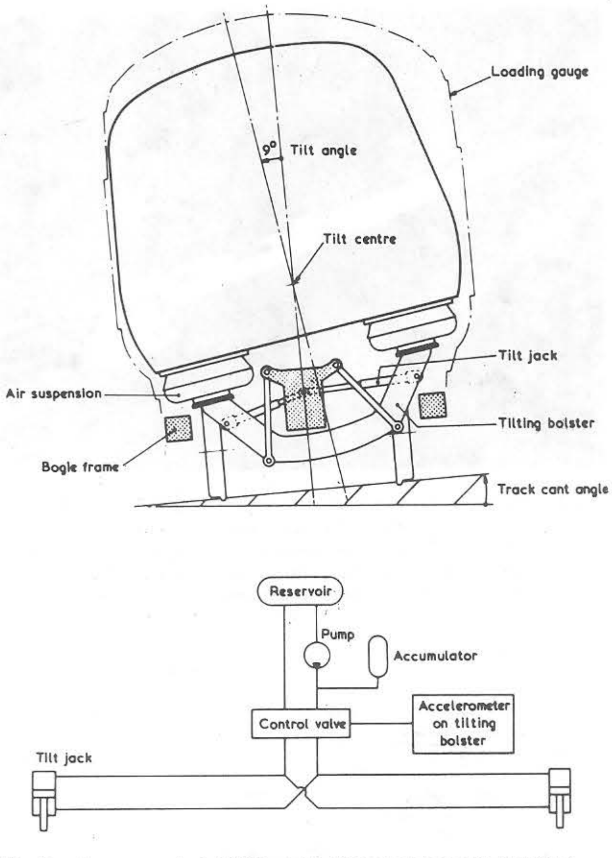

Fig. 7: Arrangement of APT-P vehicle tilt suspension and simplified diagram of control system

Fig. 9: APT-E rounds the 1.15 km radius Upper Broughton curve on the test track at 195 km/h (12° cant deficiency) whilst lateral track forces and displacements are measured

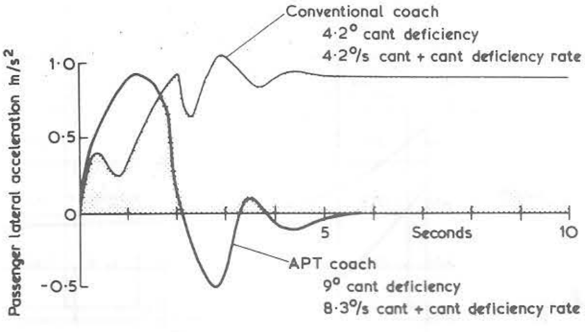

Fig. 8: Comparison of accelerations experienced by passengers during entry to curves with minimum transition lengths

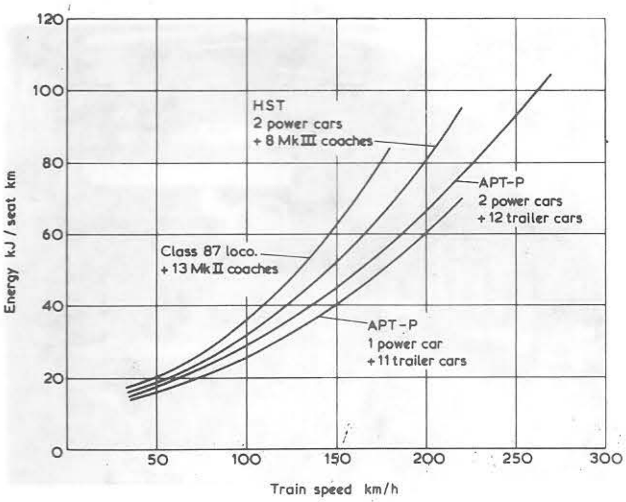

Fig. 10: Comparison of tractive energy consumptions per equivalent second-class seat. (All passenger and catering accommodation assumed to be second-class seating.)

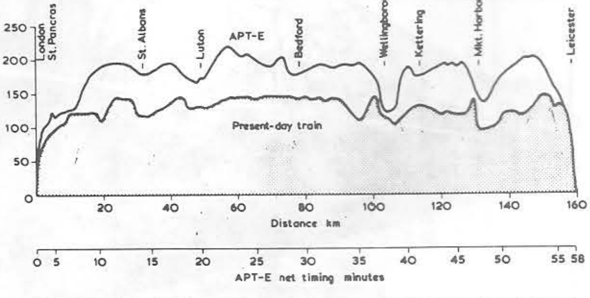

Fig. 11: Speed profiles of London to Leicester journey, showing improvement demonstrated by APT-E relative to present-day service

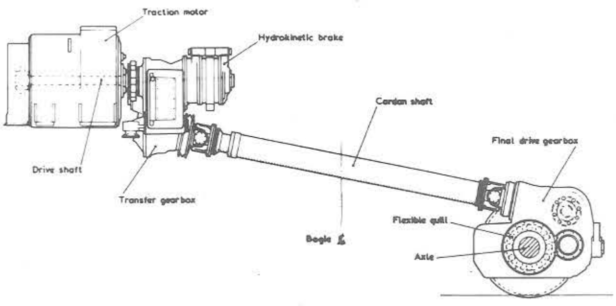

Fig. 12: APT-P mechanical transmission with body-mounted traction motor and bogie-frame-mounted final drive

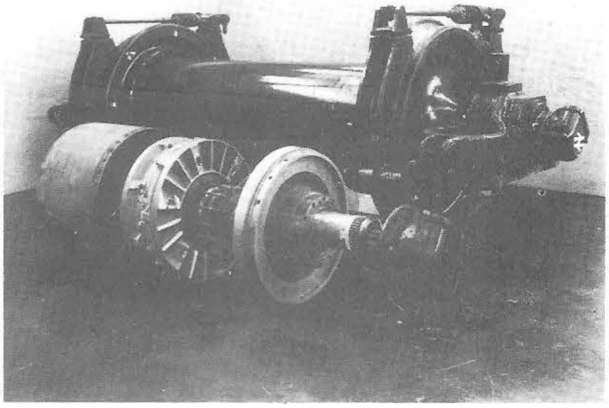

Fig. 13: The APT-E hydrokinetic brake, mounted inside a tubular trailer-axle to give low unsprung mass, contains two rotor/stator pairs for bi-directional braking. Fluid is transferred to and from the brake via a tube, which also provides torque reaction to the axlebox

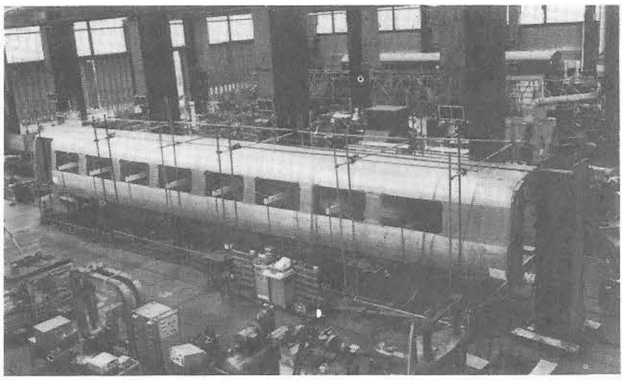

Fig. 14: The APT-P pre-production trailer car bodyshell constructed from wide aluminium-alloy extrusions being subjected to strength and stiffness tests

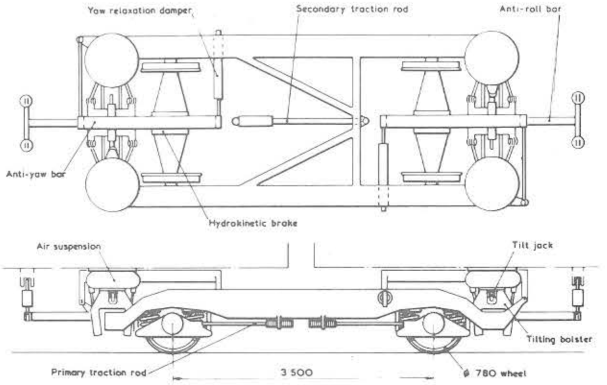

Fig. 15: The BT11 articulated bogie provides independent suspensions for adjacent vehicle bodies – design axle-load is 140 kN

200 km/h (1 + 11) low-powered version

250 km/h (2 + 12) high-powered version (prototype)

250 km/h (2 + 14) stretched version

Fig. 16: Alternative versions of the 25 kV electric APT